EEG SOURCE LOCALIZATION SENSITIVITY DUE TO BRAIN LESIONS MODELING ERRORS

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Abstract- **For accurate electroencephalogram-based (EEG) localization of neural sources correct modeling of brain lesions geometry and tissue conductivity is required. Lesion properties are derived from anatomical images like CT or MRI. According to imaging modality, lesion can appear of different size and shape. Conductivity parameters are taken from standard references, despite the large variability in the available data. The uncertainties in lesion conductivity assignment (LCA) and in determining exact lesion geometry affect source localization accuracy. The aim of this paper is to quantify the combined effect of these uncertainties on EEG dipole source localization accuracy. The study was conducted using an eccentric-spheres model of the head in which a modifiable eccentric bubble approximated various brain lesions. In 32 simulated pathological conditions the inverse dipole fitting procedure was carried out assuming an incorrect (under/overestimate) lesion dimension and conductivity. Errors in lesion modeling led to markedly wrong source reconstruction even for small differences between the actual lesion and its model. Localization errors up to 15.4 mm demonstrate the requirement of an accurate parametric setting of the model to achieve localization accuracy within few millimeters.**

Keywords **– Electroencephalography, dipole localization, imaging, inhomogeneity, inverse problems, source localization**

I. INTRODUCTION

Source localization techniques based on scalp-recorded electroencephalography (EEG) use measurements of electric scalp potentials to noninvasively estimate the localization of underlying neural activity with unsurpassed temporal resolution. Such information is of interest for both research and clinical applications as preoperative planning or epilepsy [1]. EEG source estimation requires the assumption of a source model and of a volume conductor model that describes the electrical and geometrical properties of the human head. Commonly used source models are dipole models, for which the parameters are position, orientation and strength. The single electric current-dipole is a suitable source model for the early components of the evoked potentials [2] and the epileptic focus [3]. By using the volume conductor model of the head, the potentials generated by a current source at a known position in the brain can be computed (bioelectric forward problem). For any given source model, the parameters of the neural source can be estimated from the EEGs measured at the scalp (bioelectric inverse problem). From source knowledge it is possible to map the electrical activity of the brain.

Head-modeling errors produced by differences between the actual head and the head model cause source localization errors (i.e., the distance between the estimated source and the actual source). One of the factors that influence the accuracy of EEG source localization is the large uncertainty in the conductivity of most head tissues. This uncertainty is reflected by the wide range of values reported in the literature [4]. It should be noticed that the uncertainty in determining tissue conductivity values is particularly large for brain lesions, because of the poor statistics available [5]. Lesions can have various shapes and their electrical property are largely variable and undetermined. Brain lesions may have a much higher conductivity than brain tissue (an oedema) or a much lower one (calcification). Neglecting such inhomogeneities in the conductor head model would alter source localization in the peri-lesion area, precluding clinical applications like a conservative neurosurgery based on EEG functional mapping [6]. Brain lesion conductivity values range from 0.52 to 1.89 S/m for a liquid lesion, and from 0.0018 to 0.0070 S/m for a calcified lesion. An error on lesion conductivity assignment may lead to a location of the reconstructed source far away from the "real source". Thus, we must account for errors in lesion conductivity assignment [7].

With the availability of magnetic resonance imaging (MRI) and computed tomography (CT) it is now possible to detect the presence of lesions in the brain. Both these imaging techniques derive information about lesion morphology from the volumetric distribution of some tissue properties (e.g. X-ray specific absorbing or relaxation time). None of them directly maps either the electrical conductivity of tissues or tissues geometry; in fact the same tissue/organ might appear rather different with the two different approaches, or even within the same modality changing the contrast mechanism (see Fig.1). A map of head volume conductivity (the head model) is required to solve bioelectric problems; such a map is built postulating a strict correlation between bioimages (i.e. CT or MRI maps) and conductivity map. For this reason head models depend on which anatomical images are available: a comparative example is shown in Figure 1. The difference is particularly evident for structures, like lesions, of unpredictable shape and properties. MRI is often preferred to CT for lesion diagnosis because it is more sensitive in soft tissue discrimination; CT is used to study the other tissues.

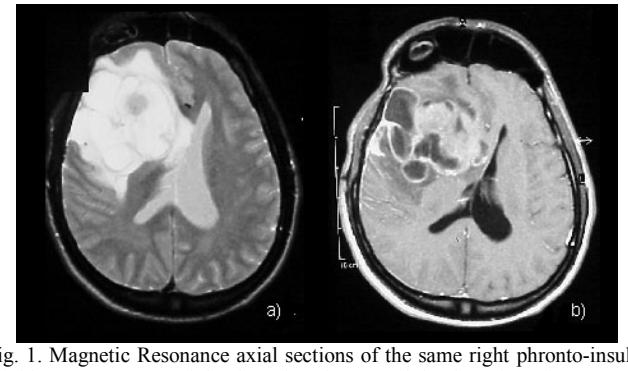

Fig. 1. Magnetic Resonance axial sections of the same right phronto-insular glioblastoma: a) T2-weighted section; b) T1-weighted section after contrast medium injection.

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Abstract

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Clearly, accurate description of structure like the head, in which hard and soft tissues are mixed, benefits from integration of information from both bioimaging modalities. Unfortunately this is not always possible, e.g. because the MR can not be used with patients with pacemaker. Thus, either because conductivity distribution differs from the specific bioimage map or because the diagnostic tool is not the best, we must account for errors in lesion dimension assignment. We present here a sensitivity study of the effect of the combined uncertainty in determining exact brain lesions dimension and conductivity estimates on EEG single dipole source localization. The study is conducted using a modified spherical model of the head (eccentric-spheres model) valid also in pathological conditions [6]. Although spherical head models are only an approximation to an actual head, the benefit arising from simplified calculations justifies their use in many situations. Since our aim was to evaluate the effect of lesion dimension and conductivity mispecification on dipole source localization, we could neglect the peculiar errors due to a spherical approach versus a realistic one simply comparing simulation results collected with spherical models in different situations.

II. Methodology

To investigate the effects of lesion parameters mispecification on EEG source localization accuracy we simulated many EEG scalp-potential distributions in presence of various brain lesions. We adopted a four-eccentric-spheres head model to account for pathological conditions, in which the eccentric bubble represents a brain lesion (see Figure 2) [6]. The model contains eight parameters, four sphere radii and four compartment conductivities [4], [8] as shown in Table I. The lesion radius was kept variable to simulate different lesion dimensions; the distance of the center of the bubble from the center of the head was considered variable to study the effect of lesion site.

We simulated the presence of several different brain lesions and various focal brain activities. Dipole amplitude has been kept constant through all simulations (50 μA·m). The analytic calculation for the EEG potential has been performed using previously developed mathematical methods [9]. Scalp potential was sampled on 128 virtual electrodes evenly spaced on the scalp (covering the area between inion and mastoid).

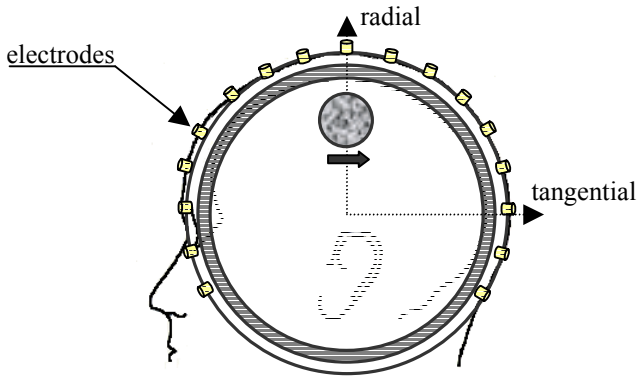

Fig. 2. Pathologic head model: the concentric spheres represent, outside to inside, scalp, skull and brain; the eccentric bubble simulates a lesion in the brain; the bold arrow indicates the dipole source.

We evaluated 32 different pathologic conditions, by comparing the scalp potentials for: 1) different pathology (different conductivity of the bubble relative to that of the surrounding region: σrel=3 to represent a fluid lesion; σrel=0.01 for a calcified tumor); 2) dimension of the lesion: the radius of the bubble was varied to simulate a small (8 mm) or a large (15 mm) brain lesion; 3) positions for the dipole source respect to the lesion: far (40 mm from lesion center); above and near (1 mm from the border); internal (2 mm from the inner border); below and near (1 mm from the border); 4) dipole orientations: tangential and radial (see Figure 2).This study has been conducted using the following procedure. First, the potential at the electrode positions was simulated in the above-described situations adopting baseline values for model compartments parameters shown in Table I (32 conditions). An equivalent dipole-source for each (simulated) EEG distribution was then calculated (the inverse problem solution) by means of a least-squares fit between the simulated measured potentials and the potential distribution calculated using the head model in which lesion dimension and conductivity were misestimated. In other words, forward and inverse calculations were carried out with different lesion dimension and conductivity values, leaving all the other parameters unchanged. Source reconstruction accuracy was quantified by the localization error (LE). LE was defined as the distance (difference) between the known real source position and the reconstructed source position. We spanned conductivity from 50% to 200% of baseline value by 50% baseline conductivity steps (see Table I), totaling 4 cases for each of the 32 situations.

TABLE I:
BASELINE GEOMETRIC (RADII) AND ELECTRICAL (CONDUCTIVITY) CHARACTERISTICS OF THE COMPARTMENTS OF THE MODEL AND RANGE OF ESTIMATION OF RADIUS AND CONDUCTIVITY LESION PARAMETERS. MISESTIMATION OF LESION DIMENSION IS QUANTIFIED AS LESION DIMENSION ERROR DE = ESTIMATED RADIUS - ACTUAL BASELINE RADIUS ..

Compartment			**Baseline values**		**Dimension misestimation**				**Conductivity misestimation**	
			Radius (mm)	*Conductivity (S/m)*	*Min Radius (mm)*		*Max Radius (mm)*		*Lower bound (S/m)*	*Upper bound (S/m)*
					Radius	*DE*	*Radius*	*DE*		
Scalp			80	0.3500						
Skull			75	0.0220						
Brain			70	0.3300						
Lesion	Fluid	Small	8	0.9900	4	-4	17	+9	0.495	1.98
		Large	15	0.9900	7	-8	20	+5	0.495	1.98
	Calcified	Small	8	0.0033	4	-4	17	+9	0.00165	0.0066
		Large	15	0.0033	7	-8	20	+5	0.00165	0.0066

We repeated this procedure for 14 lesion dimension estimations: lesion radius adopted in source localization procedure ranged from a minimum to a maximum value (see details in Table I) by steps of 1 mm, thus computing 1792 source locations. By this way we were able to determine the sensitivity of the dipole inverse solution position to both the geometrical and conductivity parameters of the eccentric-spheres model.

III. Results

The maximum absolute localization error found considering only lesion conductivity estimate (LCA) error was 8.2 mm and that considering only lesion dimension estimate error (DE) was of 10.4 mm. The former was found (see line +100% at DE= 0 in Fig. 3) simulating a large superficial fluid lesion interposed between a radial source and the electrodes (condition below); the latter was found (see line 0% at DE= -8 in Fig. 4) simulating a large superficial calcified lesion within which an internal radial dipole generated the scalp potentials. The maximum absolute localization error raised to 15.4 mm considering both lesion conductivity estimate and lesion dimension estimate errors (see line +100% at DE= 5 in Fig. 3). In this case, the maximum error due to lesion dimension estimate error only was 9.0 mm (see line 0% at DE= -8 in Fig. 3).

Figs. 3, 4, 5 and 6 show examples of LE committed considering both LCA error and lesion dimension error DE. These examples show also many characteristics of LE sensitivity to lesion parameters uncertainties.

LE for calcified lesions is substantially independent on LCA error (curves overlap) and it depends only on dimension error in all cases (see Fig. 4). For calcified lesions LE is more sensitive to overestimation of lesion dimension than to its underestimation. For negative DEs curves tend to saturate towards large LE values (even for small DEs). Conversely, LE increases together with size overestimation.

For fluid lesions, combined LCA and positive dimension errors cause the larger LEs. For positive DEs, LE increases with both LCA and DE. Negative DE values bring to more overlapping curves, demonstrating a reduced sensitivity to LCA (see Fig. 3). A neural source deep in the brain and far apart from the lesion (fluid only) is sensitive to size and conductivity overestimation (see Fig. 5).

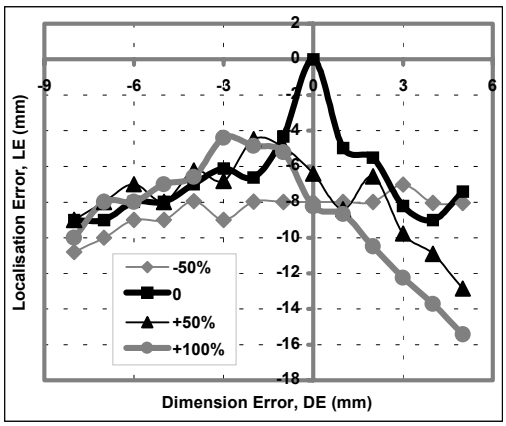

Fig. 3. Localization error for a radial source below a large, superficial, fluid lesion. Curves refer to different lesion conductivity assignments (LCA). See legend, percentages refer to baseline values.

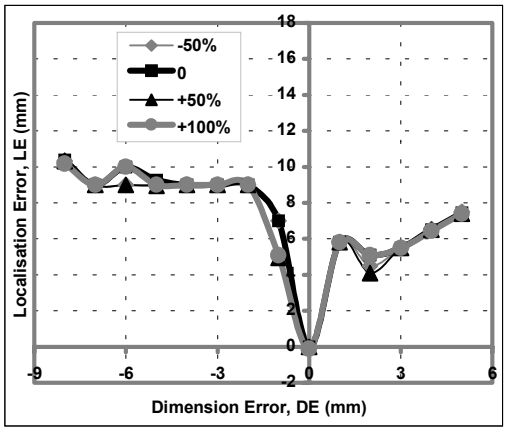

Fig. 4. Localization error for a radial source internal to a large, superficial, calcified lesion. Curves refer to different lesion conductivity assignment (LCA). See legend, percentages refer to baseline values.

For positive DEs, greater the LCA error, smaller the DE for which LE starts to increase rapidly. Errors in small lesion parameter estimation show similar trends and values to those found for large lesions (see Fig. 6). For both large and small lesions, the rapid increase of LEs was found for a source-lesion distance of about 20 mm (this distance decreases as a side effect of overestimating lesion dimension).Data not shown in figures reveal similar properties for LE sensitivity but with LE values within 10 mm and commonly smaller than few mm. Comparative data analysis indicates also that if the source is placed between lesion and electrodes LE is bound to about 6 mm, i.e. the accuracy of source reconstruction method is less sensitive to lesion parameters uncertainty. LEs in presence of calcified lesions are less sensitive to dipole orientation (tangential or radial source) than in presence of fluid lesions. Table II summarizes results obtained for large and superficial lesions. Deep lesions determine smaller errors than superficial lesions. For smaller lesions the trends were similar but, in general, localization errors were also smaller.

IV. Discussion

In previous studies [7], [10], where we analyzed separately the localization error due to lesion conductivity uncertainty and that due to lesion dimension estimate error, we found errors of 17 and 19 mm respectively, meanwhile in the present work those errors were reduced of about 50% (8.2 and 10.4 mm respectively). The error reduction is due to a different sampling of the scalp potentials (128 vs. 64 electrodes covering a larger scalp area). This is not a surprising effect since the effect of measurement montage on source reconstruction accuracy is a known problem [11]. The analysis of the condition for which we found the maximum absolute localization error (15.4 mm) demonstrated that, at least in specific condition, localization error is formed by addition of one error due to conductivity and of another due to dimension. For positive DEs we found a general trend indicating that LE sensitivity increases combining sources of errors. This can be explained considering that a larger inhomogeneity alters the relative position of lesion and source, which fall relatively closer in the volume conductor. LE was found to be sometimes independent to lesion conductivity assignment error and/or to dimension error.

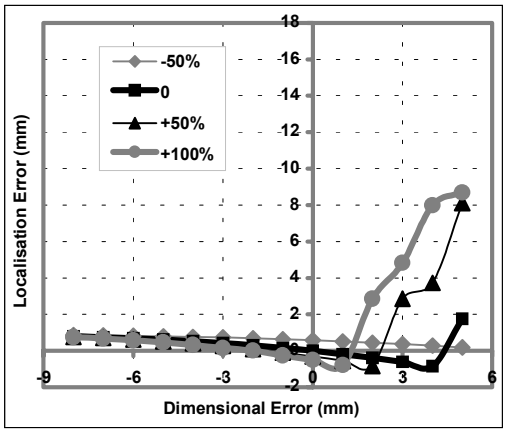

Fig. 5. Localization error for a radial source below and far (40mm) a large, superficial, fluid lesion. Curves refer to different lesion conductivity assignment (LCA). See legend, percentages refer to baseline values.

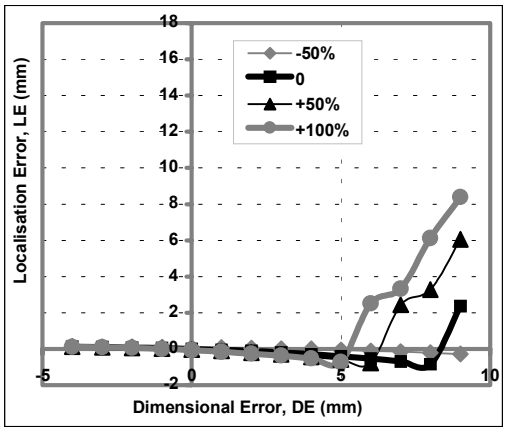

Fig. 6. Localization error for a radial source below and far (40mm) a small, superficial, fluid lesion. Curves refer to different lesion conductivity assignment (LCA). See legend, percentages refer to baseline values.

TABLE II
ABSOLUTE LE ERRORS FOR LARGE AND SUPERFICIAL LESIONS. CONDITION CODES: X-Y-Z HAVE THE FOLLOWING MEANING: X:3 FLUID, 0.01 CALCIFIED, Y: A ABOVE, B BELOW, I INTERNAL, F FAR; Z: T TANGENTIAL, R RADIAL. LCAE: LCA ERROR.

Condition	DE (mm)	LCAE (%)	Abs(LE) (mm)
3-A-t	5	100	3.8
3-I-t	-8	-50	8.0
3-B-t	-1	-50	5.3
3-F-t	5	100	-4.8
3-A-r	5	100	5.1
3-I-r	-8	-50	-10.25
3-B-r	5	100	-15.4
3-F-r	5	100	8.68
0.01-A-t	-1	50	-4.2
0.01-I-t	5	-50	8.1
0.01-B-t	-8	100	5.8
0.01-F-t	5	100	-0.8
0.01-A-r	-6	50	6.2
0.01-I-r	-8	0	10.4
0.01-B-r	5	-50	-4.6
0.01-F-r	5	100	-3.0

Since the source can not be accurately reconstructed assuming an inadequate head model, this means that LE might be compensated by source intensity error. For calcified lesion the independence of LE from LCA demonstrates that a sort of error compensation does not occur. On the contrary, for fluid lesion the most critical situations are either those of contemporary overestimation of size and conductivity of the lesion or the contemporary underestimation of them (see Table II); in this situation, lesion error compensation can be achieved and LE reduced. Our data analysis indicates that, in general, a wise approach would be to underestimate the lesion conductivity parameter (not precisely known). See for example Fig. 3: even for the largest DE, LE can decrease from about 16 mm to 8 mm underestimating lesion conductivity.

Finally we want to remind that the solution of the inverse problem is found solving an iterative procedure: an initial estimate of the parameters for the chosen source model is made, the resulting potential field is calculated using the adopted head model, the calculated field is compared with the measured one and the source parameters are adjusted accordingly. The simultaneous presence of several sources of errors often determines convergence problems due to the presence of local minima in the solution space. Further studies are needed to investigate the sensitivity of the algorithm to model parameter accuracy.

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